

EFFECT OF IMPACTING MASS ON FIRMNESS SENSING OF FRUITS

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ABSTRACT. *There has been an increased interest in using impact techniques for sensing firmness of fruits and vegetables. When an impactor is used to strike a fruit, the impacting mass is an important parameter which affects both the impact signal and fruit damage. Results of theoretical analyses and tests conducted on two varieties of pears indicate that lowering the impacting mass results in amplifying the measured signal, reducing sensing errors, and minimizing damage to the fruit. Keywords.* Impact, Fruit firmness, Quality evaluation, Sorting, Nondestructive, Pears.

The force response of an elastic sphere impacting a rigid surface is governed by the impacting velocity, mass, radius of curvature, elastic modulus, and Poisson's ratio of the sphere. Researchers have found that the impact of a fruit on a rigid surface can be closely modeled by the impact of an elastic sphere and that the firmness of a fruit has a direct effect on the impact force response. Nahir et al. (1986) reported that when tomatoes are dropped from a 70 mm height onto a rigid surface, the impact force response is highly correlated with fruit mass and fruit firmness. They subsequently developed an experimental tomato grading machine which, by measuring and analyzing the impact force response of the fruit, could separate tomatoes on the basis of mass and color. Delwiche et al. (1987) analyzed impact forces of peaches striking a rigid surface and found that certain impact force characteristics were highly correlated with the fruit's elastic modulus and penetrometer measurements of flesh firmness. A single lane firmness sorting system was developed which used the index F/t^2 (where F and t are the peak impact force and the time required to reach peak force, respectively) to sort peaches and pears into hard, firm, and soft categories (Delwiche et al., 1989). A problem inherent to the technique of dropping the fruit on a force sensor is that the impact force is also a function of the mass and radius of curvature of the fruit. Therefore, a large variation in these two parameters will affect the accuracy in firmness measurement.

A different approach is to impact the fruit with a small spherical impactor of known mass and radius of curvature and measure the acceleration of the impactor. The advantage of this method is that the measured impact-acceleration response is independent of the fruit mass and

is less sensitive to the variation of the radius of curvature of the fruit. This technique was first described by Chen et al. (1985) and was used by researchers in Spain for sensing fruit firmness (Jarén et al., 1992; Correa et al., 1992). Ruiz-Altisent et al. (1993) developed a system which used the impact parameters to classify fruits (apples, pears, and avocados) into different firmness groups. They used a 50-g impactor with a 19-mm-diameter spherical tip, dropping from a height of 3 cm for apples and 4 cm for pears and avocados.

When an impactor is used to impact a fruit, the mass of the impactor is an important parameter which affects both the impact signal and fruit damage. The objective of this study is to determine theoretically and experimentally the effect of the impacting mass on firmness sensing of fruits.

THEORETICAL DEVELOPMENT

A number of researchers have shown that when a fruit is subjected to a high-rate loading such as that which occurs during an impact, the elastic model can be used to determine the effects of various parameters on the response of the fruit (Horsfield et al., 1972; Jindal and Mohsenin, 1976; Delwiche, 1987). The impact of a spherical impactor on a fruit can be modeled by the impact of a rigid sphere on an elastic sphere. In such an impact, the dynamic response of the impactor is a function of the elastic modulus and Poisson's ratio of the elastic sphere, and the masses, radii of curvatures, and the relative (approaching) velocity of the two objects. Based on the theoretical analysis of two impacting elastic spheres given by Timoshenko and Goodier (1951), the magnitude of the peak impact force, F , acting on each body can be expressed as:

$$F = \left(\frac{5}{4} \frac{V^2}{n_1} \right)^{3/5} n_1^{2/5} \quad (1)$$

where

V = relative velocity of approach of both spheres

$$n_1 = \frac{m_1 + m_2}{m_1 m_2}$$

$$n = \frac{4}{3} \frac{E}{(1-\mu^2)} \left[\frac{R_1 R_2}{(R_1 + R_2)} \right]^{1/2}$$

m_1 = mass of impactor

m_2 = mass of fruit

R_1 = radius of impactor

R_2 = radius of curvature of fruit surface

μ = Poisson's ratio of fruit

E = modulus of elasticity of fruit

The maximum deformation, D , of the fruit can be written as:

$$D = \left(\frac{5}{4} \frac{V^2}{n \mu} \right)^{2/5} \quad (2)$$

And the time required to reach peak force can be expressed as:

$$t = 1.47 D/V \quad (3)$$

Assuming negligible gravitational effect during impact (about two percent), one can express the peak acceleration, A , of the impactor as:

$$A = F/m_i \quad (4)$$

$$= \left(\frac{5}{4} V^2 \right)^{0.6} \frac{1}{m_2} \left[\frac{m_1 m_2}{(m_1 + m_2)} \right]^{0.6} \left[\frac{4}{3} \frac{E}{(1-\mu^2)} \right]^{0.4} \left[\frac{R_1 R_2}{(R_1 + R_2)} \right]^{0.2}$$

The ratio of A/t , often used as a firmness index, can be expressed as follows:

$$A/t = 0.68 FV/Dm_i \quad (5)$$

$$= 0.8954 V^{1.4} \frac{1}{m_1} \left[\frac{m_1 m_2}{(m_1 + m_2)} \right]^{0.2} \left[\frac{E}{(1-\mu^2)} \right]^{0.8} \left[\frac{R_1 R_2}{(R_1 + R_2)} \right]^{0.4}$$

EXPERIMENTAL PROCEDURE

Tests were conducted to compare the results of firmness sensing obtained with three impactors of different masses. An impact tester (fig. 1) similar to that described by Chen et al. (1985) was used. For all three tests the impactor had a 19-mm-diameter spherical tip. The impacting mass,

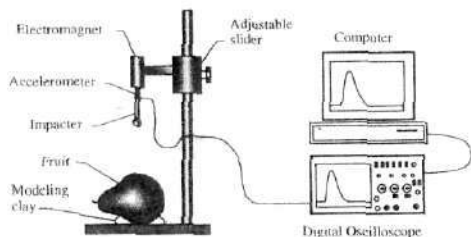


Figure 1—Impact testing system.

drop height, and acceleration history were recorded for each impact. Two experiments were conducted—one at the Polytechnic University in Madrid, Spain, and one at the University of California, Davis.

TEST PROCEDURE IN SPAIN

'Conferencia' pears harvested from a commercial orchard were taken to the Agricultural Engineering laboratory in Madrid. One box of 30 fruits was stored at 20°C and another box of 30 fruits was stored at 0°C in order to produce a range of fruit firmness. After three days all 60 fruits were brought out from storage, and impact tests were made after the fruits equilibrated to room temperature. Four impacts were made at four locations along the largest circumference of the fruit using two impactors of 20- and 50-g mass, respectively, and two drop heights of 2 and 4 cm for both impactors. The two impacts of the same drop height (but different impactor masses) were made at two adjacent points about 15 mm apart, and the 2-cm impacts were made on the opposite side of the fruit from the 4-cm impacts. During the impact test, the fruit was set on modeling clay on top of a rigid steel plate. Preliminary tests of impacting tightly held (by hand) and not-held fruits showed no differences in the acquired acceleration signals. Therefore, the fruits were not held in subsequent tests.

Fruit firmness (not flesh failure strength as measured by the Magness-Taylor method) was measured by compressing the fruit with a 19-mm-diameter spherical indenter at a deformation rate of 20 mm/min. The deformation at 10 N compression force was recorded, and the elastic modulus, E , was determined from the following equation (Timoshenko and Goodier, 1951):

$$E = \frac{3}{4} \frac{F(1-\mu^2)}{D^{1.5}} \left(\frac{R_1 + R_2}{R_1 R_2} \right)^{0.5} \quad (6)$$

The values of μ and R_2 were assumed constant at 0.49 (as suggested by Fridley et al., 1968) and 35 mm, respectively. A constant value of 35 mm for R_2 was used because it can be shown that when R_1 is 9.5 mm, a variation of the value of R_2 within a reasonable range of real fruit size, say from 35 to 40 mm, results in only a very small error (1.3 %) in E .

TEST PROCEDURE IN CALIFORNIA

'Bartlett' pears harvested from a commercial orchard in Lake County were taken to Davis. One box of approximately 30 fruits was stored at 20°C and a second box was stored at 0°C. After two days the first box was also moved into the 0°C room. After both boxes were stored at 0°C for an additional week, they were moved into the 20°C room, and five fruits from each box were taken out on the first, third, and fifth days for testing. Impact tests were similar to those made in Spain except that the mass of the lighter impactor was 10 g instead of 20 g. Fruit firmness was measured by compressing the fruit with a 9.5-mm-diameter spherical indenter at a deformation rate of 100 mm/min. The compression force at 1.0 mm was used to calculate the value of E using equation 6.

RESULTS AND DISCUSSION

RESULTS OF THEORETICAL ANALYSIS

The following parameters were used in the theoretical analysis: $R_1 = 0.01$ m; $R_2 = 0.035$ m; $\mu_2 = 0.49$; $V = 0.886$ m/s (equivalent to a 4-cm drop height); $E = 0.7$ MPa for soft fruit and 7.0 MPa for firm fruit; $m_2 = 0.2$ kg for free-to-move fruit and 10 000 kg (∞) for fixed fruit.

On the basis of these parameters and equation 1, we calculated the values of peak force for different impacting masses when they were dropped onto a soft and a firm fruit. Figure 2 shows that, as the impacting mass varies from 10 to 50 g, the peak force on the soft fruit increases from 6.3 to 14.8 N, and the peak force on the firm fruit increases from 16.2 to 42.5 N. Since high impact force is associated with fruit damage, this result suggests that a light impactor should be used to avoid fruit damage. Figure 2 also shows that the difference between the peak force on a fixed fruit and that on a free-to-move fruit diminishes as the impacting mass decreases from 50 to 10 g.

The values of peak acceleration, A , calculated from equation 4, were plotted in figure 3. The peak acceleration increases from 850 to 1 618 m/s^2 when the impacting mass is reduced from 50 to 10 g for the firm fruit. Since the acceleration signal is the primary measured parameter in firmness sensing, it is desirable to use a lighter impactor because it generates a stronger acceleration signal that is easier to detect and has higher signal-to-noise ratio. In addition to the increase in acceleration, the spread between the peak acceleration obtained with the soft fruit and that obtained with the firm fruit also increases as the impacting mass decreases. This is another desirable feature for firmness sensing.

Figure 3 also shows an acceleration curve for a firm fruit that is allowed to move freely during the impact (not fixed). The difference between this curve and that of the fixed fruit decreases as the impacting mass decreases, indicating that the error due to a small movement of the fruit is less critical when a smaller impacting mass is used. This factor is quite important for on-line sorting, where it is difficult to hold the fruit stationary during the impact

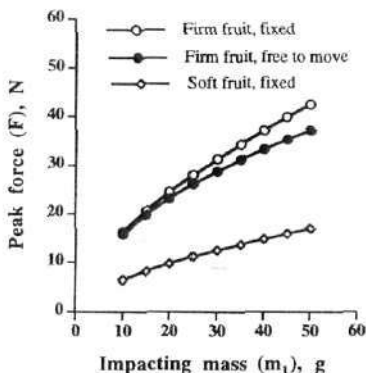


Figure 2—Relationship between theoretically calculated peak force and impacting mass.

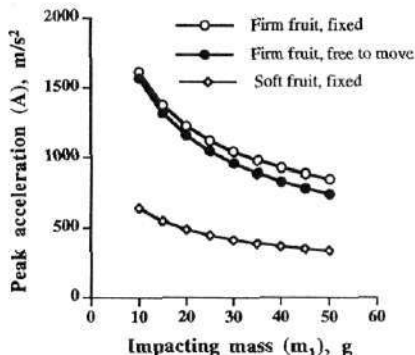


Figure 3—Relationship between theoretically calculated peak acceleration and impacting mass.

sensing. A similar trend (not plotted) was also found for the soft fruit.

The impacting mass has an even greater effect on the firmness index A/t (fig. 4). The values of A/t for both the firm and soft fruits, as well as the spread of A/t between the two fruits, increase more than threefold when the impacting mass is reduced from 50 to 10 g. Clearly the firmness index is more sensitive to the change in fruit firmness when a lighter impactor is used. The closeness between the curve for the fixed fruit and that for the free-to-move fruit indicates that the firmness index, A/t , is not sensitive to how the fruit is held during impact sensing.

EXPERIMENTAL RESULTS

The results of tests on Bartlett pears are shown in figures 5 and 6. Figure 5 shows the relationships between peak acceleration and the firmness (E value) of the fruits for the four combinations of impacting mass and drop height. For the same drop height the peak acceleration of the 10-g impactor is about twice as high as that of the 50-g impactor. In addition, the slope of the regression line,

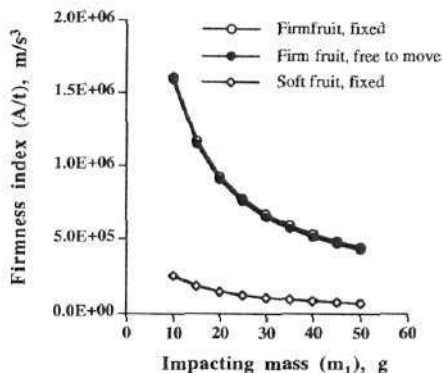


Figure 4—Relationship between theoretically calculated firmness index, A/t , and impacting mass.

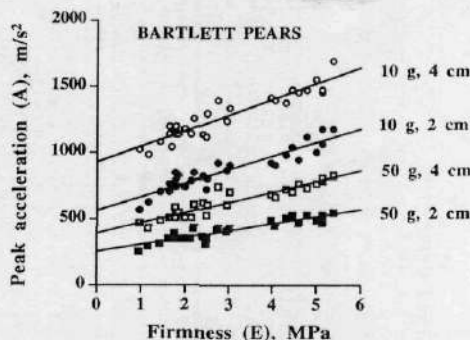


Figure 5—Results of tests on Bartlett pears showing the relationship between peak acceleration and fruit firmness, E.

which is the rate of change of the acceleration with respect to fruit firmness, for the 10-g impacting mass is greater than that for the 50-g mass.

Figure 6 shows the relationships between the firmness index, A/t , and the E value. For each drop height, the value of A/t obtained with the 10-g impactor is about three times as large as that obtained with the 50-g impactor, and the rate of change of A/t with respect to E for the 10-g impactor is about three times as high as that for the 50-g impactor (table 1).

Similar results were also obtained from tests conducted in Spain with Conferencia pears. Figure 7 and table 1 show similar increases in both the values of A/t and the slopes of the regression lines as the impacting mass was reduced from 50 to 20 g.

Table 1 presents a summary of the experimental results. The 10-g impactor did not cause any damage to any of the Bartlett pears tested. The 20-g impactor did not bruise any Conferencia pears at 2-cm drop height, but bruised 26% of the fruits at 4-cm drop height. The 50-g impactor damaged 32% of the Conferencia pears and 53% of the Bartlett pears when it was dropped from a 2-cm distance. At the 4 cm

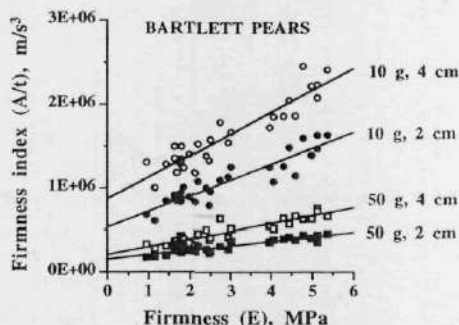


Figure 6—Results of tests on Bartlett pears showing the relationship between firmness index, A/t , and fruit firmness, E.

Table 1. Summary of experimental results*

Variety	Impacting Mass (g)	Drop Height (cm)	Bruised Fruit (%)	Intercept (m/s^3)	Slope ($m/s^3/MPa$)	R^2
Conferencia	20	2	0	3.59×10^5	0.167	0.78
	20	4	26	8.16×10^5	0.182	0.73
	50	2	32	1.71×10^5	0.059	0.78
	50	4	79	3.40×10^5	0.073	0.63
Bartlett	10	2	0	5.26×10^5	0.189	0.85
	10	4	0	8.66×10^5	0.259	0.87
	50	2	53	1.53×10^5	0.053	0.84
	50	4	89	2.06×10^5	0.092	0.84

* The values of intercept, slope, and R^2 correspond to the regression lines in figures 6 and 7.

drop height, nearly all of the fruits were bruised by the 50-g impactor. The value of A/t for a bruised fruit is difficult to predict. Since bruising tends to occur at high A, and a bruise will generally cause a drop in the value of A, a large number of bruised fruits in a data set will result in a decrease in the slope of the regression line in figure 7 (e.g., for the cases of 50-g impactor dropping from 2 and 4 cm, and 20-g impactor dropping from 4 cm).

The result in table 1 shows that lighter impactors can be dropped from a greater height without causing fruit damage. Since the error in drop height setting is a constant absolute value (e.g., ± 1 mm), the ability to increase the drop height would further reduce sensing errors.

CONCLUSIONS

Both theoretical and experimental results point to the following desirable features associated with low impacting mass:

- Increases strength of the measured acceleration signal, thereby facilitating easier detection and maximizing noise-to-signal ratio.
- Increases both the magnitude of the calculated firmness index, A/t , and the rate of change of A/t with respect to the fruit firmness, E.
- Minimizes the error due to movement of the fruit during the impact.
- Minimizes fruit damage caused by the impact.

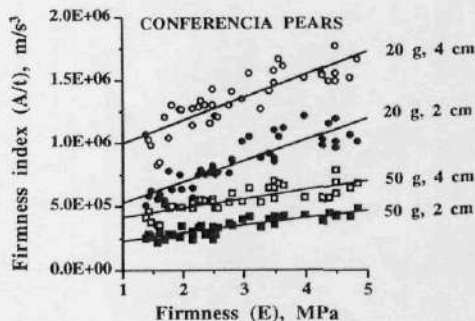


Figure 7—Results of tests on Conferencia pears showing the relationship between firmness index, A/t , and fruit firmness, E.

APPLICATION OF FINDINGS

The results of this study suggest that in firmness sensing of fruits where the acceleration of an impactor is measured, the mass of the impactor should be kept as low as possible. The minimum value of the impacting mass may be limited by several factors. First, it is limited by the mass of the accelerometer. For example, for a 2-g accelerometer, like the one used in this study, the mass of the impactor would be limited to 3 to 4 g. Second, it is limited by the ability to control the impacting velocity. Since the acceleration signal must be transmitted from the moving accelerometer to a recording device, the size and stiffness of the electrical cable would affect the ability to control the impacting velocity. As shown in equation 5, the impacting velocity, V , has the strongest effect on the firmness index, A/t . Therefore, it is important to maintain a constant impacting velocity on every fruit on the sorting line. Third, the minimum value of the impacting mass is limited by the amount of material required to provide adequate structural integrity of the impactor. The impactor should be rigid enough so that it will not produce undesired vibration that may interfere with the acceleration signal.

The proper values of impacting mass and drop height (or impacting velocity) depend on the physical design of the sensing unit (free-fall, sliding, or swinging impactor, and means for transmitting the acceleration signal) and the type of fruit being tested. The general approach is to aim at the lowest impacting mass and the highest impacting velocity. We recommend the following design procedure: Design an impactor such that it can generate the same impacting velocity on different fruits; then reduce the impactor mass as much as possible while still maintaining the control of the impacting velocity and structural integrity of the impactor; and, finally, increase the impacting velocity until it is just below the threshold of bruising the fruit.

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